FACULTY OF ENGINEERING AND ARCHITECTURE

ELECTRONICS AND INFORMATION SYSTEMS DEPARTMENT
LIQUID CRYSTALS AND PHOTONICS RESEARCH GROUP

LIQUID CRYSTALS AND LIGHT EMITTING MATERIALS FOR PHOTONIC APPLICATIONS

Kristiaan Neyts April 2018 Lecture series at WAT in Warsaw

GHENT UNIVERSITY

nb-photonics
Center for Nano- and Biophotonics
Ghent University

Liquid Crystals and Photonics

OVERVIEW

Liquid crystal properties (10h)

Properties of nematic liquid crystals
Nematic order parameter
Polarization and dielectric constant
Elastic energy
Surface alignment
Electrical energy
Freederickz treshold
VAN mode
Variable phase retarder
IPS mode
TN mode

Liquid Crystals and Photonics

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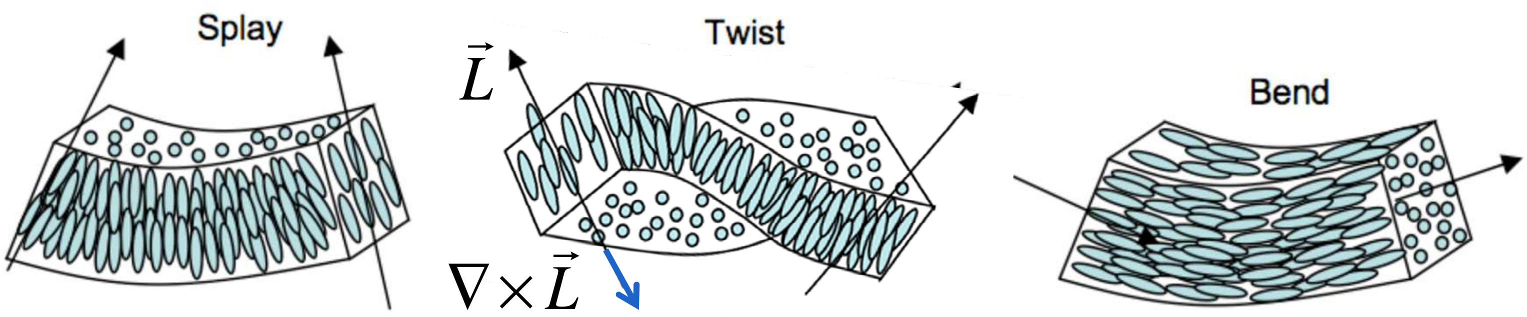
ELASTIC ENERGY

Elastic energy for chiral liquid crystal

lowest energy when: $\vec{L}\cdot\left(\nabla\times\vec{L}\right)=-q_0$ right handed CLC: $q_0>0$

$$f_{elastic}=\frac{1}{2}\left[K_{11}\left(\nabla\cdot\vec{L}\right)^2+K_{22}\left(\vec{L}\cdot\left(\nabla\times\vec{L}\right)+q_0\right)^2+K_{33}\left(\vec{L}\times\left(\nabla\times\vec{L}\right)\right)^2\right]$$



right handed twist

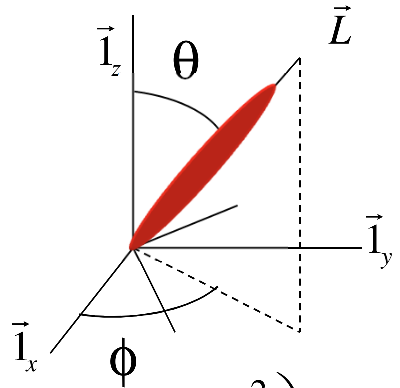
$$\vec{L}\cdot\left(\nabla\times\vec{L}\right)<0$$

ELASTIC ENERGY

In a **1D geometry** (*L* depending only on *z*)

$$\vec{L} = \begin{pmatrix} \cos\phi(z)\sin\theta(z) \\ \sin\phi(z)\sin\theta(z) \\ \cos\theta(z) \end{pmatrix}$$

only $\dfrac{\partial}{\partial z}$



$$f_{elastic} = \tfrac{1}{2}\left(K_{11}\left(\nabla\cdot\vec{L}\right)^2 + K_{22}\left(\vec{L}\cdot\left(\nabla\times\vec{L}\right)\right)^2 + K_{33}\left(\vec{L}\times\left(\nabla\times\vec{L}\right)\right)^2 \right)$$

after calculation: ...

$$f_{elastic} = \tfrac{1}{2}\left(K_{11}\left(\sin\theta\frac{\partial\theta}{\partial z}\right)^2 + K_{22}\left(\sin^2\theta\frac{\partial\phi}{\partial z}\right)^2 + K_{33}\left(\left(\cos\theta\frac{\partial\theta}{\partial z}\right)^2 + \left(\cos\theta\sin\theta\frac{\partial\phi}{\partial z}\right)^2\right)\right)$$

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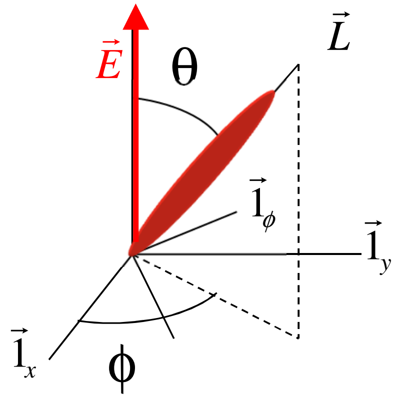
ELECTRIC ENERGY

Electric energy density (with source)

$$f_{electric} = -\tfrac{1}{2}\vec{D}\cdot\vec{E} = -\tfrac{1}{2}\left(\overline{\overline{\varepsilon}}\vec{E}\right)\vec{E} = -\tfrac{1}{2}\varepsilon_{\perp}E^{2} - \tfrac{1}{2}\Delta\varepsilon\left(\vec{L}\cdot\vec{E}\right)^{2}$$

$$\overline{\overline{\varepsilon}}\vec{E} = \varepsilon_{\perp}\vec{E} + \Delta\varepsilon\left(\vec{L}\vec{L}\right)\vec{E} = \varepsilon_{\perp}\vec{E} + \Delta\varepsilon\vec{L}\left(\vec{L}\cdot\vec{E}\right)$$

$$\begin{cases} \vec{L}\cdot\vec{E} = E\cos\theta \\ \vec{L}\times\vec{E} = -E\sin\theta\,\vec{1}_{\phi} \end{cases}$$



given field E (for example V/d)

Δε>0: lowest energy when L and E are parallel

Δε<0: lowest energy when L and E are perpendicular

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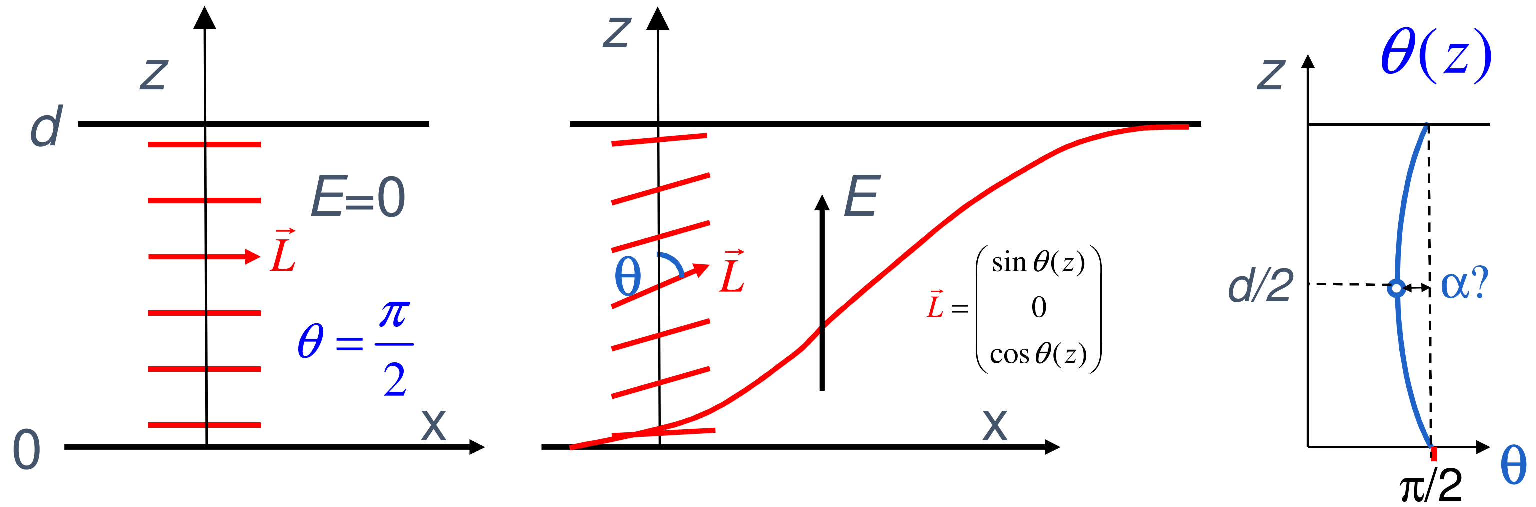
EXAMPLE: FRÉEDERICKSZ TRANSITION

LC between substrates with *E*-field, $\phi = 0$: $\theta(z)$?



assume small deviation $\alpha \ll 1$ due to *E*-field

with given *z*-dependency: $\theta(z) = \frac{\pi}{2} - \alpha \sin\frac{\pi z}{d}$

$$\begin{cases} \cos\theta(z) = \cos\left(\frac{\pi}{2} - \alpha\sin\frac{\pi z}{d}\right) = \sin\left(\alpha\sin\frac{\pi z}{d}\right) \approx \alpha\sin\frac{\pi z}{d} \ll 1 \\ \sin\theta(z) \approx 1 \end{cases}$$

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EXAMPLE: FRÉEDERICKSZ TRANSITION

$$\theta(z) = \frac{\pi}{2} - \alpha \sin \frac{\pi z}{d}$$

calculation of elastic energy

$$f_{elastic} = \tfrac{1}{2} K_{11} \left(\sin\theta \frac{\partial \theta}{\partial z} \right)^2 + \tfrac{1}{2} K_{33} \left(\cos\theta \frac{\partial \theta}{\partial z} \right)^2$$

cos θ <<1

$$\Rightarrow F_{elastic} \approx \int_0^d \tfrac{1}{2} K_{11} \left(-\alpha \frac{\pi}{d} \cdot \cos \frac{\pi z}{d} \right)^2 dz = \tfrac{1}{4} K_{11} \alpha^2 \frac{\pi^2}{d}$$

calculation of electric energy

field approximately homogeneous: *E=V/d*

$$f_{electric} = -\tfrac{1}{2} \varepsilon_\perp E^2 - \tfrac{1}{2} \Delta\varepsilon \left(\vec{E} \cdot \vec{L} \right)^2 = -\tfrac{1}{2} \varepsilon_\perp \frac{V^2}{d^2} - \tfrac{1}{2} \Delta\varepsilon \left(\frac{V}{d} \cos\theta \right)^2$$

$$\Rightarrow F_{electric} \approx \int_0^d \left[-\tfrac{1}{2} \varepsilon_\perp \left(\frac{V}{d} \right)^2 - \tfrac{1}{2} \Delta\varepsilon \left(\frac{V}{d} \cdot \alpha \sin \frac{\pi z}{d} \right)^2 \right] dz = -\tfrac{1}{2} \varepsilon_\perp \frac{V^2}{d} - \tfrac{1}{4} \Delta\varepsilon \cdot \alpha^2 \frac{V^2}{d}$$

EXAMPLE: FRÉEDERICKSZ TRANSITION

calculation of the total energy

$$\theta(z) = \frac{\pi}{2} - \alpha \sin\frac{\pi z}{d}$$

$$F_{elastic} \approx \tfrac{1}{4} K_{11} \alpha^2 \frac{\pi^2}{d}$$

$$F_{electric} \approx -\tfrac{1}{2}\varepsilon_{\perp}\frac{V^2}{d} - \tfrac{1}{4}\Delta\varepsilon \cdot \alpha^2 \frac{V^2}{d}$$

⇨ Minimum of the total energy, for which α?

$$\frac{\partial}{\partial\alpha}\left(F_{elastic} + F_{electric}\right) \approx \tfrac{1}{2} K_{11}\alpha\frac{\pi^2}{d} - \tfrac{1}{2}\Delta\varepsilon \cdot \alpha\frac{V_{th}^2}{d} = 0$$

⇨ $$V_{th} = \sqrt{\frac{K_{11}}{\Delta\varepsilon}} \cdot \pi$$

Fréedericksz threshold

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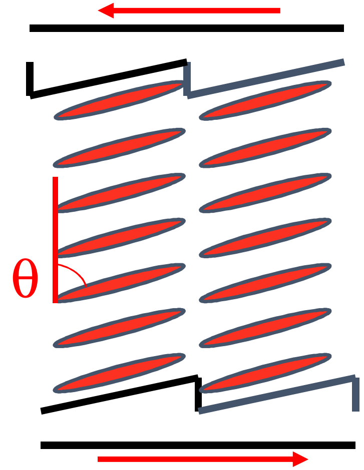
VARIABLE PHASE RETARDER

low voltage: no switching

y polarized light: n_o

x polarized light: n_e

$$\Delta n = n_e - n_0 \qquad \Gamma = \frac{2\pi\, \Delta n\, d}{\lambda}$$

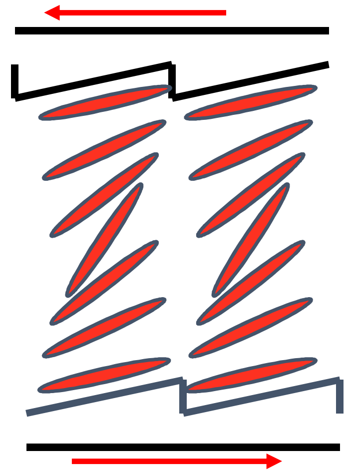


high voltage:

y polarized light: n_o

x polarized light: $n_{eff}(z)$

$$V > V_{th} = \sqrt{\frac{K_{11}}{\Delta\varepsilon}} \cdot \pi$$



$$n_{avg} = \frac{1}{d}\int_0^d \left(\frac{\cos^2\theta(z)}{n_o^2} + \frac{\sin^2\theta(z)}{n_e^2} \right)^{-\frac{1}{2}} dz$$

$$\Delta n_{avg} = n_{eff,avg} - n_0 \qquad \Gamma = \frac{2\pi \Delta n_{avg}\, d}{\lambda}$$

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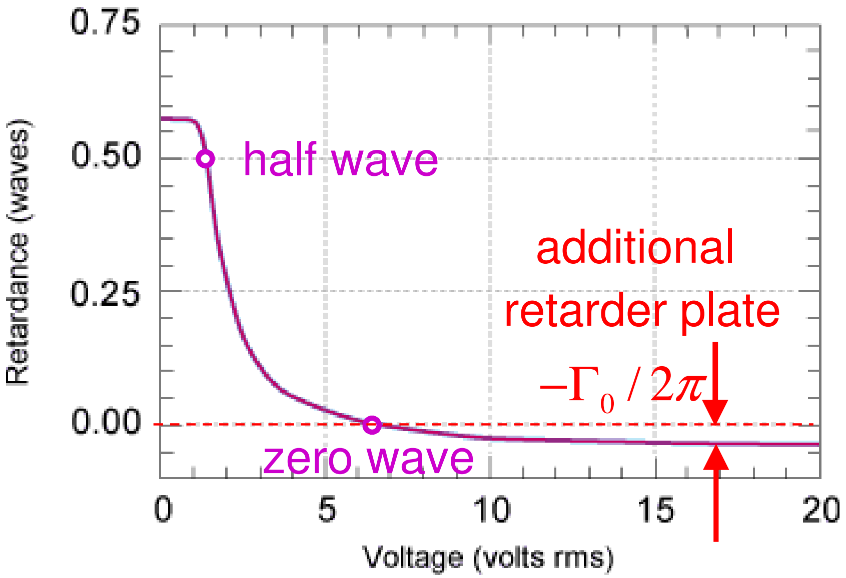
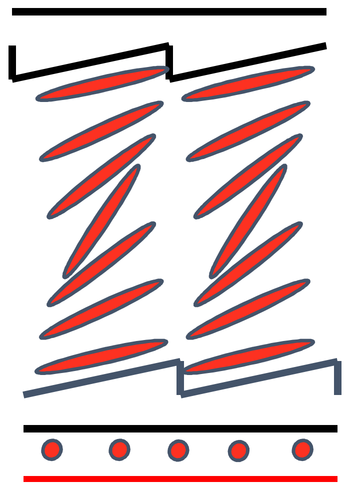
VARIABLE PHASE RETARDER

total retardation: LC retardation + plate

$$\frac{\Gamma_{tot}}{2\pi} = \frac{\Delta n_{avg}\, d}{\lambda} - \frac{\Gamma_0}{2\pi}$$



$$V > V_{th} = \sqrt{\frac{K_{11}}{\Delta\varepsilon}} \cdot \pi$$



additional
retarder plate
slow axis
perpendicular

$$-\frac{\Gamma_0}{2\pi}$$

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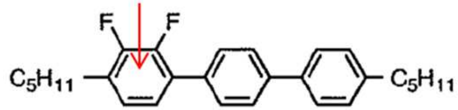
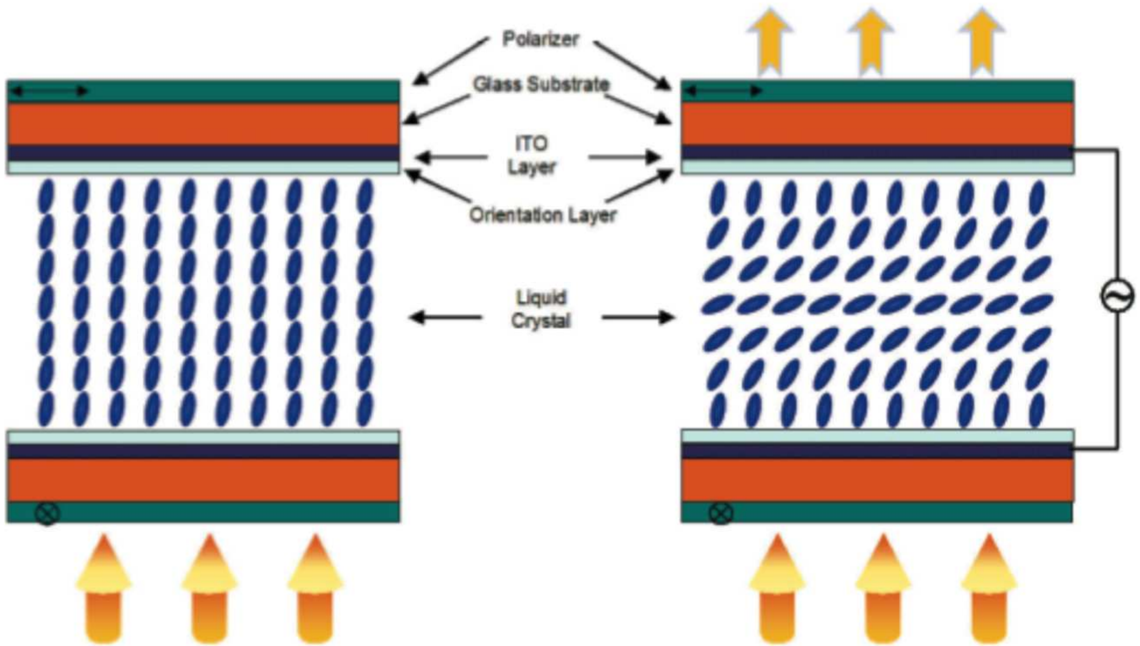
VERTICALLY ALIGNED NETMATIC (VAN)

Initially vertically aligned, and $\Delta\varepsilon < 0$
with particular alignment material

$\bar{p}$ $\beta = 90^o$





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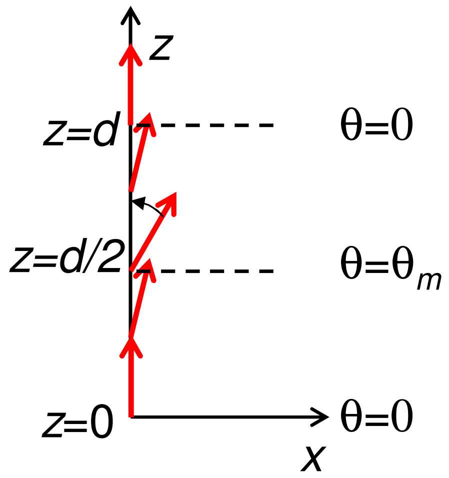
VERTICALLY ALIGNED NEMATIC (VAN)

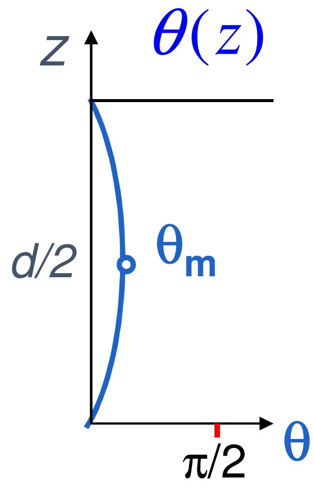
Small variation of the angle θ

suggestion:

$$\theta = \theta_m \sin\left(\frac{\pi z}{d}\right)$$

$$\varphi = 0$$
$$\theta_m << 1$$
$$\sin\theta << 1$$
$$\cos\theta \approx 1$$





$$f_{elastic} = \tfrac{1}{2}\left(K_{11}\left(\sin\theta\frac{\partial\theta}{\partial z}\right)^2 + K_{22}\left(\sin^2\theta\frac{\partial\phi}{\partial z} - q_0\right)^2 + K_{33}\left(\left(\cos\theta\frac{\partial\theta}{\partial z}\right)^2 + \left(\cos\theta\sin\theta\frac{\partial\phi}{\partial z}\right)^2\right)\right)$$

$$F_{elastic} = \tfrac{1}{2}K_{33}A\int_0^d \left(\frac{\partial\theta}{\partial z}\right)^2 dz = \tfrac{1}{2}K_{33}A\int_0^d \left(\theta_m\frac{\pi}{d}\cos\left(\frac{\pi z}{d}\right)\right)^2 dz$$

$$= \tfrac{1}{2}K_{33}Ad\left(\theta_m\frac{\pi}{d}\right)^2 \tfrac{1}{2} = \tfrac{1}{4}K_{33}A\,\theta_m^2\frac{\pi^2}{d}$$

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VERTICALLY ALIGNED NEMATIC (VAN)

Variation of the angle θ

$$\theta = \theta_m \sin\left(\frac{\pi z}{d}\right)$$

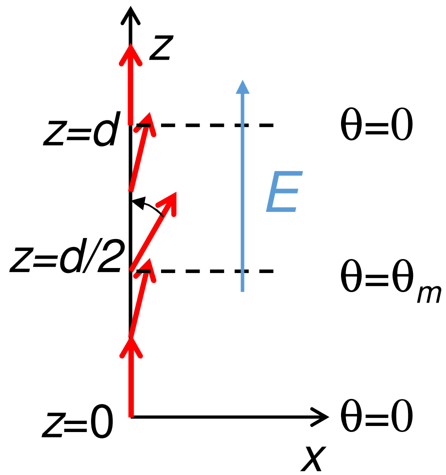
$$\varphi = 0$$

$$\theta_m << 1$$

$$\sin\theta \approx \theta << 1$$

$$\Delta\varepsilon < 0$$

$$\cos\theta \approx 1 - \frac{\theta^2}{2}$$



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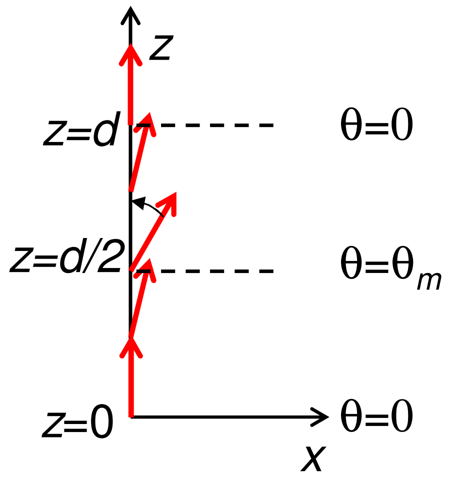
$$F_{electric} = -\tfrac{1}{2} A \int_0^d \left(\varepsilon_\perp + \Delta\varepsilon \cos^2\theta\right) E^2 dz = -\tfrac{1}{2} A \int_0^d \left(\varepsilon_\perp + \Delta\varepsilon\left[1 - \left(\theta_m \cos\left(\frac{\pi z}{d}\right)\right)^2\right]\right) \frac{V^2}{d^2} dz$$

$$= -\tfrac{1}{2} A \int_0^d \left(\varepsilon_\parallel - \Delta\varepsilon\left(\theta_m \cos\left(\frac{\pi z}{d}\right)\right)^2\right) \frac{V^2}{d^2} dz = -\tfrac{1}{2} A\varepsilon_\parallel \frac{V^2}{d^2} d + \tfrac{1}{2} A\Delta\varepsilon\theta_m^2 \frac{V^2}{d^2}\left(d\,\tfrac{1}{2}\right)$$

$$= -\tfrac{1}{2} A\varepsilon_\parallel \frac{V^2}{d} - \tfrac{1}{4} A\left|\Delta\varepsilon\right|\theta_m^2 \frac{V^2}{d}$$

VERTICALLY ALIGNED NEMATIC (VAN)

$$\theta = \theta_m \sin\left(\frac{\pi z}{d}\right)$$



Does $\theta_m = 0$
minimize the total energy?

$$F_{total} = F_{elastic} + F_{electric} = \tfrac{1}{4} K_{33} A\, \theta_m^2 \frac{\pi^2}{d} - \tfrac{1}{2} A\varepsilon_{\parallel} \frac{V^2}{d} - \tfrac{1}{4} A\left|\Delta\varepsilon\right| \theta_m^2 \frac{V^2}{d}$$

$$\frac{\partial F_{total}}{\partial \theta_m} = \tfrac{1}{4} K_{33} A\, 2\theta_m \frac{\pi^2}{d} - \tfrac{1}{4} A\left|\Delta\varepsilon\right| 2\theta_m \frac{V^2}{d} = \tfrac{1}{2} A\theta_m \frac{1}{d}\left(K_{33}\pi^2 - \left|\Delta\varepsilon\right| V^2\right)$$

threshold voltage makes this zero

$$V_{TH} = \pi\sqrt{\frac{K_{33}}{\left|\Delta\varepsilon\right|}}$$

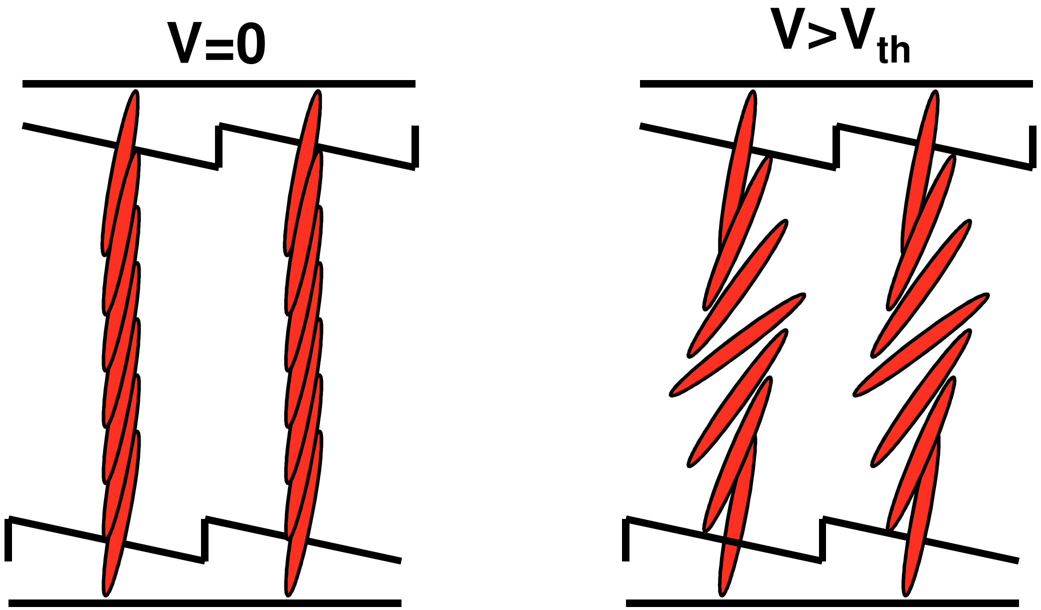
$$V < V_{TH} \rightarrow \quad \theta = 0$$

VERTICALLY ALIGNED NEMATIC (VAN)

1D structure, material with $\Delta\varepsilon < 0$, $\Delta n > 0$

homeotropic alignment

- for $V = 0$: $\theta \approx 0$ $\Gamma \approx 0$
- for $V > V_{th}$: molecules rotate: θ , Γ, Δn increase



$$V_{th} = \sqrt{\frac{K_{33}}{|\Delta\varepsilon|}} \cdot \pi$$

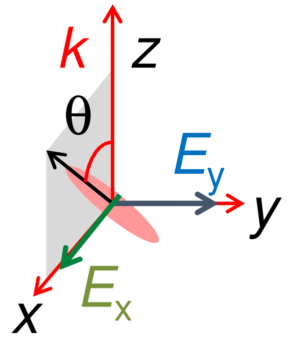
bend and splay

pretilt determines switching

LIGHT IN ANISOTROPIC MATERIALS

propagation along the *z*-axis (distance *d*)

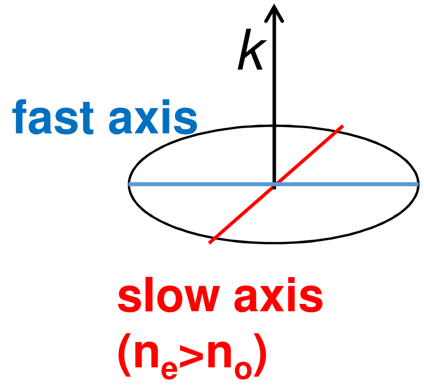
two polarizations with different speed



ordinary mode E_y : $n=n_o$

extra-ordinary mode E_x : $n=n_{eff}$

$$n_{eff}=\frac{1}{\sqrt{\frac{\cos^2\theta}{n_o^2}+\frac{\sin^2\theta}{n_e^2}}}$$



Liquid Crystals and Photonics

Jones matrix

$$\bar{\bar{J}}=\begin{bmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{i\Gamma/2} \end{bmatrix}$$

retardation

$$\Gamma=\frac{2\pi}{\lambda}\left(n_{eff}-n_o\right)d$$

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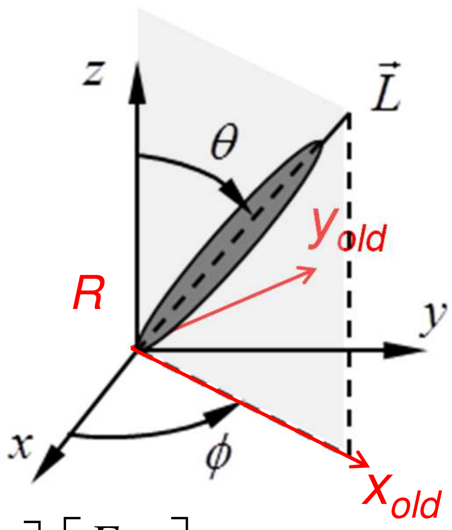
LIGHT IN ANISOTROPIC MATERIALS

Transformation of the Jones matrix for a general system of axes:



$$\overline{\overline{J}}' = R\overline{\overline{J}}_{old}R^{-1}$$

R R-1

$$\begin{bmatrix} E_{x,out} \\ E_{y,out} \end{bmatrix} = \begin{bmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{i\Gamma/2} \end{bmatrix} \cdot \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} E_{x,in} \\ E_{y,in} \end{bmatrix}$$

$$= \begin{bmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} \cos\varphi \cdot e^{-i\Gamma/2} & \sin\varphi \cdot e^{-i\Gamma/2} \\ -\sin\varphi \cdot e^{i\Gamma/2} & \cos\varphi \cdot e^{-i\Gamma/2} \end{bmatrix} \cdot \begin{bmatrix} E_{x,in} \\ E_{y,in} \end{bmatrix}$$

$$= \begin{bmatrix} \cos^2\varphi \cdot e^{-i\Gamma/2} + \sin^2\varphi \cdot e^{i\Gamma/2} & \sin\varphi\cos\varphi \cdot \left(e^{-i\Gamma/2} - e^{i\Gamma/2}\right) \\ \sin\varphi\cos\varphi \cdot \left(e^{-i\Gamma/2} - e^{i\Gamma/2}\right) & \sin^2\varphi \cdot e^{-i\Gamma/2} + \cos^2\varphi \cdot e^{i\Gamma/2} \end{bmatrix} \cdot \begin{bmatrix} E_{x,in} \\ E_{y,in} \end{bmatrix}$$

LIGHT IN ANISOTROPIC MATERIALS

$$\overline{\overline{J}} = \begin{bmatrix} \cos^2\varphi\cdot e^{-i\Gamma/2}+\sin^2\varphi\cdot e^{i\Gamma/2} & \sin\varphi\cos\varphi\cdot\left(e^{-i\Gamma/2}-e^{i\Gamma/2}\right) \\ \sin\varphi\cos\varphi\cdot\left(e^{-i\Gamma/2}-e^{i\Gamma/2}\right) & \sin^2\varphi\cdot e^{-i\Gamma/2}+\cos^2\varphi\cdot e^{i\Gamma/2} \end{bmatrix}$$

$$\begin{aligned} J_{11} &= \cos^2\varphi\cdot e^{-i\Gamma/2}+\sin^2\varphi\cdot e^{i\Gamma/2} \\ &= \cos^2\varphi\cdot\left(\cos(\Gamma/2)-i\sin(\Gamma/2)\right)+\sin^2\varphi\cdot\left(\cos(\Gamma/2)+i\sin(\Gamma/2)\right) \\ &= \left(\cos^2\varphi+\sin^2\varphi\right)\cos(\Gamma/2)+\left(-i\cos^2\varphi+i\sin^2\varphi\right)\sin(\Gamma/2) \\ &= \cos(\Gamma/2)-i\cos2\varphi\sin(\Gamma/2) \end{aligned}$$

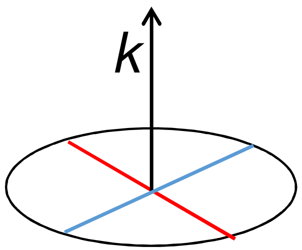
$$\begin{aligned} J_{12} &= \sin\varphi\cos\varphi\cdot\left(e^{-i\Gamma/2}-e^{i\Gamma/2}\right) \\ &= \sin\varphi\cos\varphi\cdot\left(-2i\sin(\Gamma/2)\right) \\ &= -i\sin2\varphi\cdot\sin(\Gamma/2) \end{aligned}$$

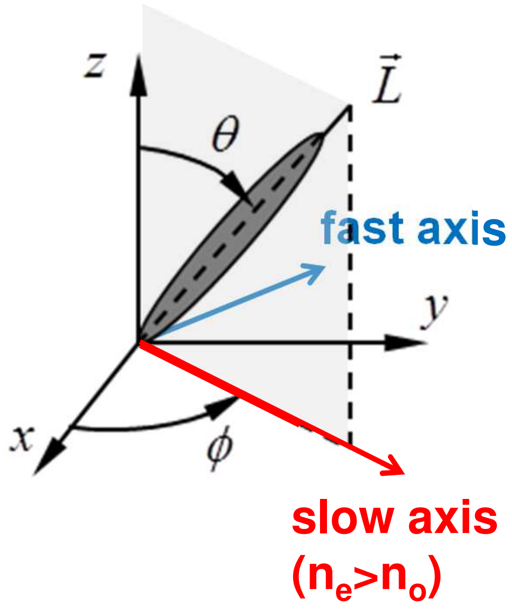
$$\overline{\overline{J}} = \begin{bmatrix} \cos(\Gamma/2)-i\cos2\varphi\sin(\Gamma/2) & -i\sin2\varphi\cdot\sin(\Gamma/2) \\ -i\sin2\varphi\cdot\sin(\Gamma/2) & \cos(\Gamma/2)+i\cos2\varphi\sin(\Gamma/2) \end{bmatrix}$$

LIGHT IN ANISOTROPIC MATERIALS

Jones matrix for a retardation plate

- retardation Γ
- azimuth φ





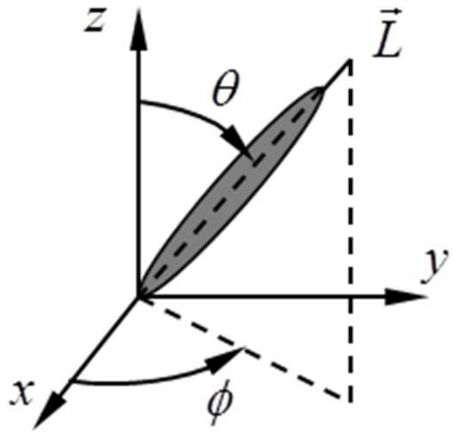
slow axis: with the highest refractive index

fast axis: with the lowest refractive index

$$\overline{\overline{J}} = \begin{bmatrix} \cos(\Gamma/2) - i\cos 2\varphi \sin(\Gamma/2) & -i\sin 2\varphi \cdot \sin(\Gamma/2) \\ -i\sin 2\varphi \cdot \sin(\Gamma/2) & \cos(\Gamma/2) + i\cos 2\varphi \sin(\Gamma/2) \end{bmatrix}$$

RETARDATION PLATES

homogeneous anisotropic layer
with given parameters



full wave plate Γ=2π

$$\bar{\bar{J}} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

independent of φ

half wave plate Γ=π

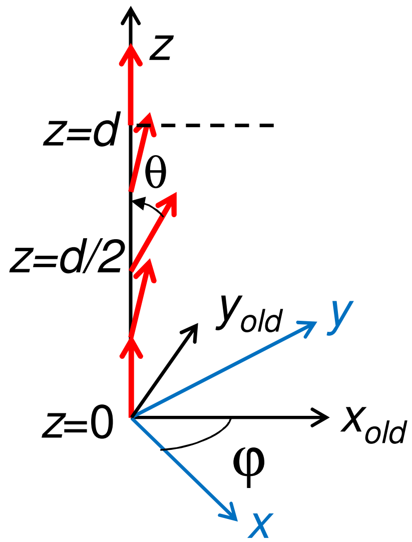
$$\bar{\bar{J}} = \begin{bmatrix} -i\cos 2\varphi & -i\sin 2\varphi \\ -i\sin 2\varphi & i\cos 2\varphi \end{bmatrix} \sim \begin{bmatrix} -\cos 2\varphi & -\sin 2\varphi \\ -\sin 2\varphi & \cos 2\varphi \end{bmatrix}$$

VERTICALLY ALIGNED NEMATIC (VAN)

Light transmission?

$$\overline{\overline{J}} = \begin{bmatrix} e^{-i\Gamma_{VA}/2} & 0 \\ 0 & e^{i\Gamma_{VA}/2} \end{bmatrix}$$

for inclination in the φ=0 plane



General case, in the plane φ:

$$\overline{\overline{J}}' = R\overline{\overline{J}}_{old}R^{-1}$$

$$\overline{\overline{J}}_{VA} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} e^{-i\Gamma_{VA}/2} & 0 \\ 0 & e^{i\Gamma_{VA}/2} \end{pmatrix} \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix}$$

$$\Gamma_{VA} = \int_0^d \frac{2\pi}{\lambda}\left(n_{eff}\left(\theta(z)\right) - n_o\right)dz = \frac{2\pi\Delta n_{avg} d}{\lambda}$$

$$n_{eff} = \frac{1}{\sqrt{\frac{\cos^2\theta}{n_o^2} + \frac{\sin^2\theta}{n_e^2}}}$$

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VERTICALLY ALIGNED NEMATIC (VAN)

With polarizer and analyzer along *x* and *y* respectively:

$$\begin{pmatrix} 0 \\ E_{out} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \overline{\overline{J}}_{VA} \begin{pmatrix} E_{in} \\ 0 \end{pmatrix}$$

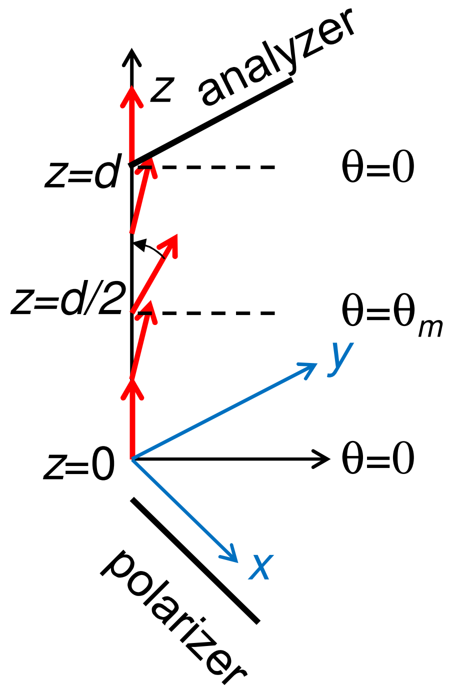
$$= \begin{pmatrix} 0 & 0 \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} e^{-i\Gamma_{VA}/2} & 0 \\ 0 & e^{i\Gamma_{VA}/2} \end{pmatrix} \begin{pmatrix} \cos\phi E_{in} \\ -\sin\phi E_{in} \end{pmatrix}$$

$$= \begin{pmatrix} 0 & 0 \\ \sin\phi \cdot e^{-i\Gamma_{VA}/2} & \cos\phi e^{i\Gamma_{VA}/2} \end{pmatrix} \begin{pmatrix} \cos\phi E_{in} \\ -\sin\phi E_{in} \end{pmatrix}$$

$$E_{out} = (-i)\sin 2\phi \sin\left(\frac{\Gamma_{VA}}{2}\right) E_{in}$$

$$T = \frac{1}{2}\sin^2 2\phi \sin^2\left(\frac{\pi \Delta n_{avg} d}{\lambda}\right)$$

for unpolarized incident light (choose $\phi=45^o$; $\Gamma_{VA}=\pi$)

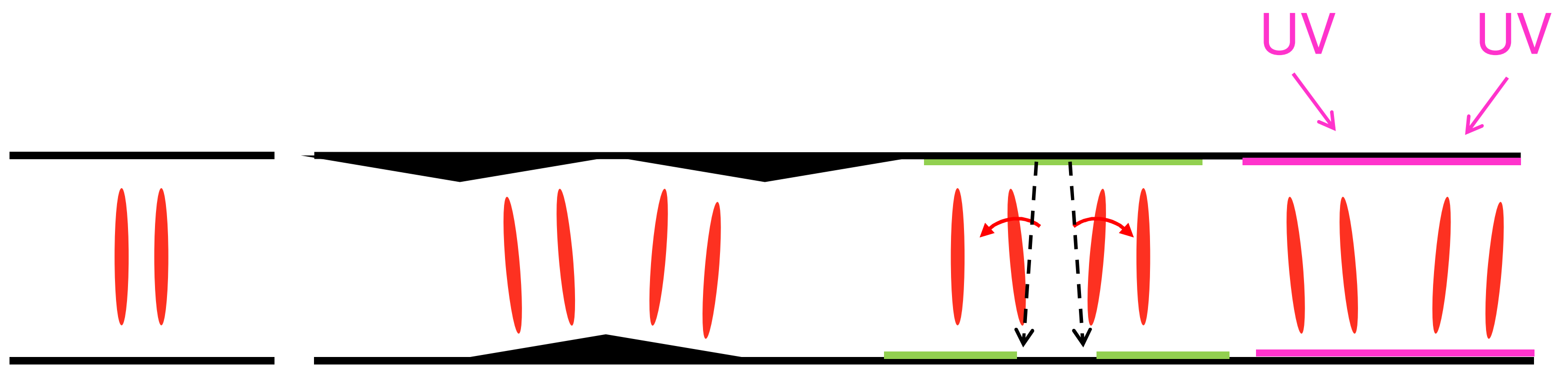


VERTICALLY ALIGNED NEMATIC (VAN)

Reproducible reorientation

how to define the azimuth ϕ of reorientation?

3 methods to determine ϕ



homeotropic alignment
ϕ not determined

protrusions

inhomogeneous electrodes and fields

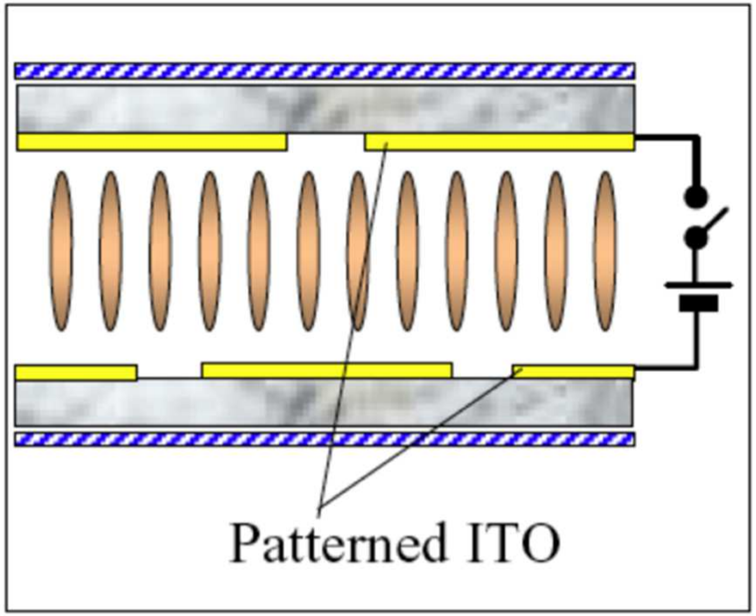
photo-aligned

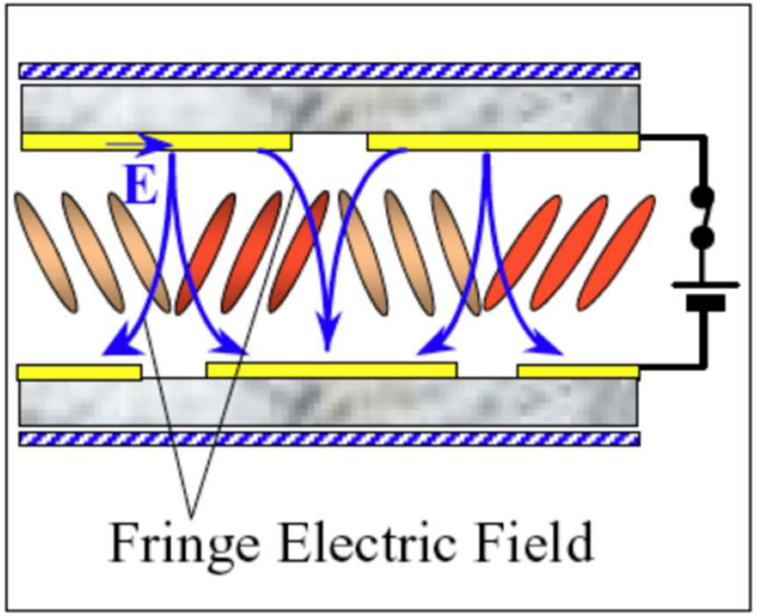
VERTICALLY ALIGNED NEMATIC (VAN)

patterned ITO electrodes (within a pixel)

lateral component of the electric field “fringe field”

determines the switching





Liquid Crystals and Photonics

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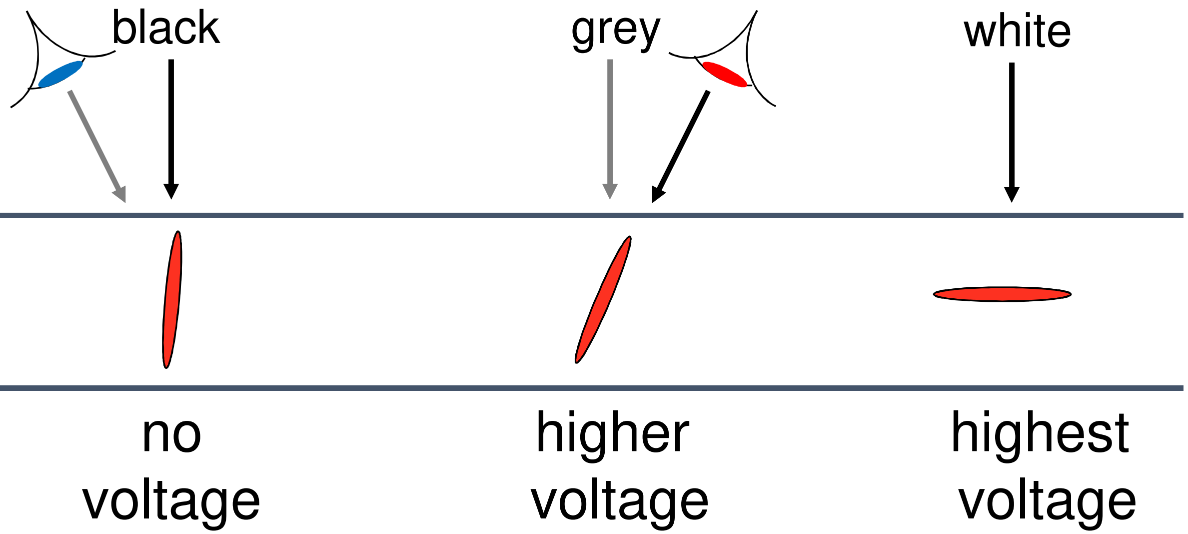
VERTICALLY ALIGNED NEMATIC (VAN)

for a direction that is not vertical

the transmission can have a different value…

black? no… grey!
bad black state,
low contrast

grey? no…black!
grey scale
inversion



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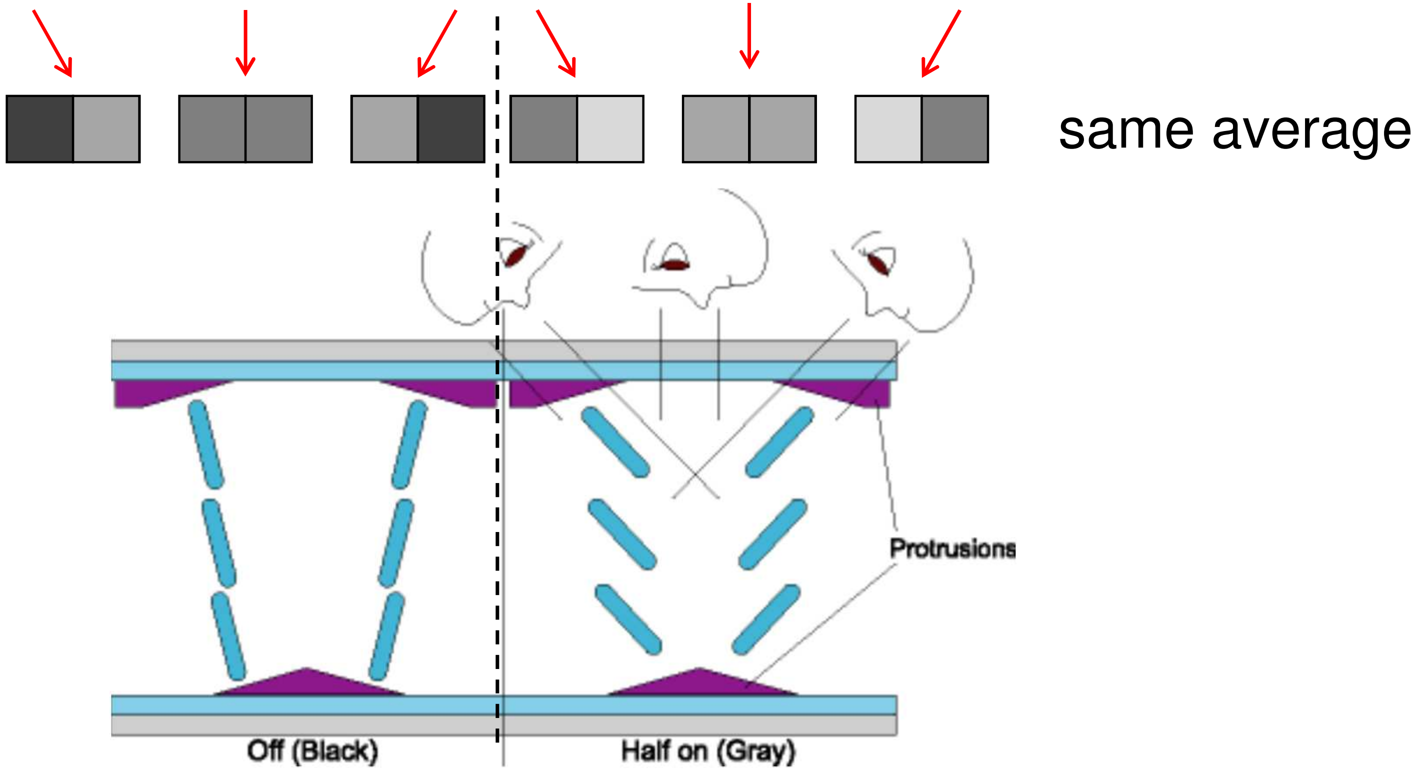
VERTICALLY ALIGNED NEMATIC (VAN)

Solving the viewing angle problem

by introducing different domains with different azimuth



Liquid Crystals and Photonics

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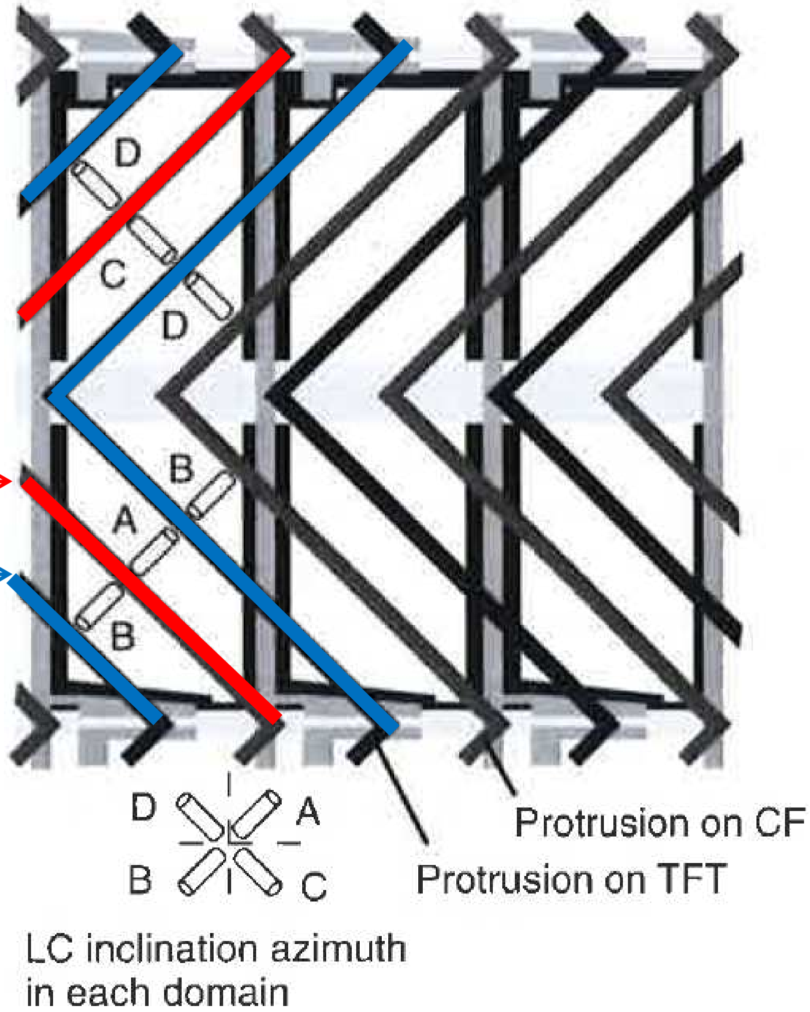
VERTICALLY ALIGNED NEMATIC (VAN)

Patterned VA
with 4 different
azimuthal angles

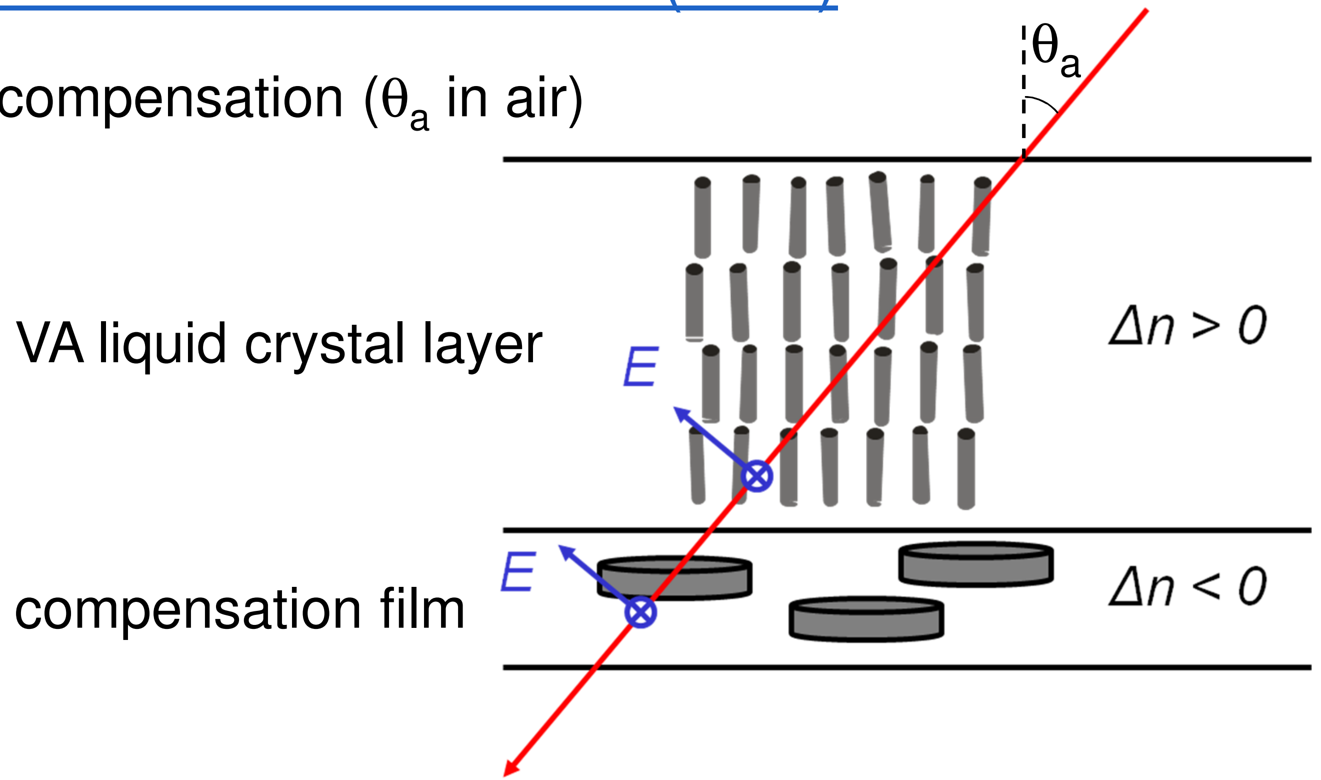
bottom substrate
protrusions on the color filters

top substrate
protrusion on TFT's



VERTICALLY ALIGNED NEMATIC (VAN)

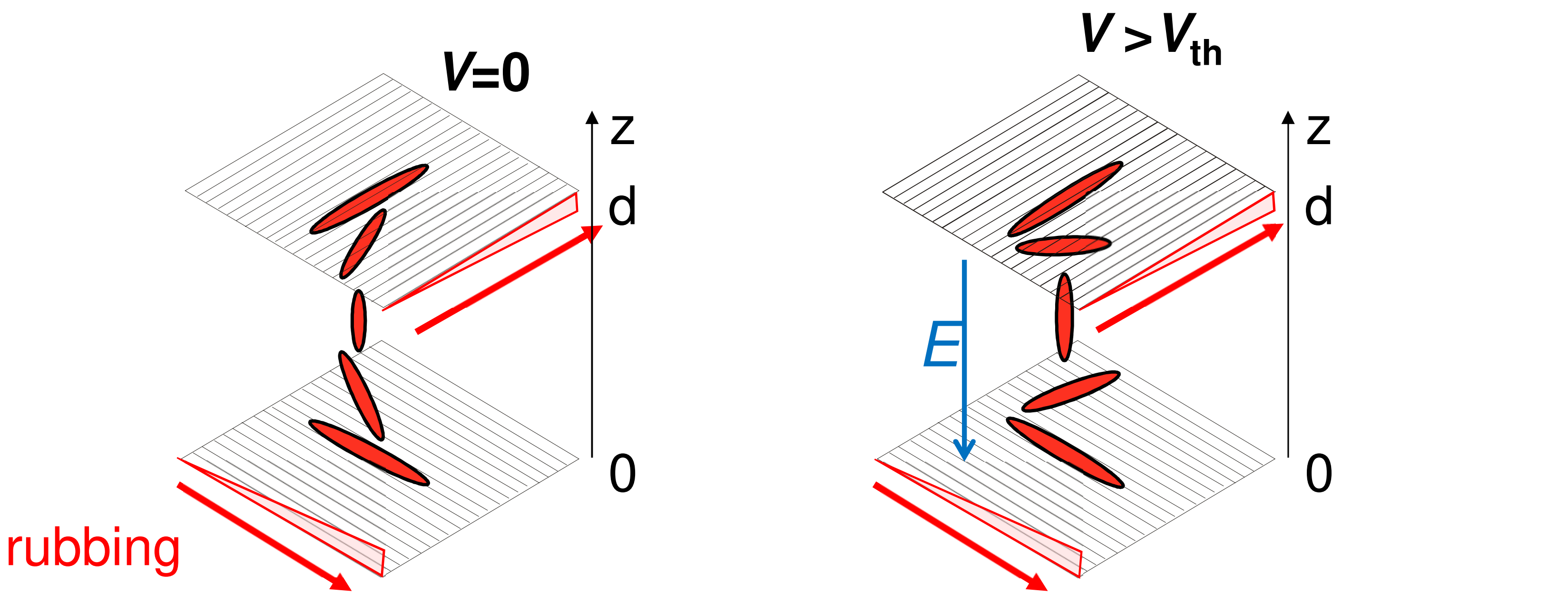
Viewing angle compensation (θ_a in air)



$$\Gamma = \frac{2\pi d_{LC}}{\lambda}\left(\sqrt{n_{eff,LC}^2 - \sin^2\theta_a} - \sqrt{n_{o,LC}^2 - \sin^2\theta_a}\right) + \frac{2\pi d_{CF}}{\lambda}\left(\sqrt{n_{eff,CF}^2 - \sin^2\theta_a} - \sqrt{n_{o,CF}^2 - \sin^2\theta_a}\right)$$

LIQUID CRYSTAL SWITCHING

Reorientation due to the torque



pretilt determines twist

$\Delta\varepsilon > 0$

director aligns parallel to the field

Liquid Crystals and Photonics

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